MEMORANDUM REPORT ARBRL-MR-02846

ONE FACTOR AFFECTING THE DISPERSION OF LONG ROD PENETRATORS

W. F. Donovan

June 1978

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
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The aerodynamic jump term is examined for application to finned projectiles. Values of static aerodynamic properties, determined by referenced tabular procedures, are compared with test data and are considered with some implications of the effects of the physical and geometric properties of the projectile. The results are presented in a generalized nomenclature based on normalized physical properties and dimensions.

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LIST OF SYMBOLS

A	$= N_1+N_2$, algebraic contraction to represent the sum of the aerodynamic normal forces
B	$= M_1+M_2$, algebraic contraction to represent the sum of the aerodynamic moments
$C_{1,2,\ldots n}$	algebraic coefficient used in the development of the modified expression for the gyroscopic stability factor
C_D	$= \dfrac{\text{Drag Force}}{\frac{1}{2}\rho v^2 S}$, zero-yaw drag coefficient
$C_{L\alpha}$	$= \dfrac{\text{Lift Force}}{\frac{1}{2}\rho v^2 S \delta}$, aerodynamic lift slope coefficient, $\delta = \sin \alpha_T$
$C_{M\alpha}$	$= \dfrac{\text{Static Moment}}{\frac{1}{2}\rho v^2 S d \delta}$, aerodynamic moment slope coefficient
$C_{N\alpha}$	$= \dfrac{\text{Normal Force}}{\frac{1}{2}\rho v^2 S \delta}$, aerodynamic normal force slope coefficient
I_x	Axial moment of inertia
I_y	Transverse moment of inertia.
J	$= J_\zeta \delta'$, aerodynamic jump term
J_ζ	$= \dfrac{I_y}{md^2} \dfrac{C_{L\alpha}}{C_{M\alpha}}$, aerodynamic jump factor
M	aerodynamic static moment
N	aerodynamic normal force
N_1	aerodynamic normal force acting on forebody
N_2	aerodynamic normal force acting on fins
ΔN	Increment in normal force as employed
S	$= \frac{\Pi}{4} d^2$, reference area

Z	$= \dfrac{1 + c\,q}{1 + q}$, accuracy ratio
c	$= \dfrac{A}{B}\,\ell_2$, algebraic coefficient employed in definition of accuracy ratio
d	body diameter, used as reference to establish linear caliber length and/or linear body dimension in reference publications
ℓ_1	distance from c.g. to forebody center of force
ℓ_2	distance from c.g. to fin center of force
α_T	total angle of attack, directed from trajectory to missile axis
δ	$= \sin \alpha_T$
δ'	initial yawing rate
ρ	air density
ρ_{ref}	reference air density

For the chart/graph symbols p (15) to p (38).

AAAC	Anti Armor Automatic Cannon
AAI	Aircraft Armaments Incorporated
AR	Aerodynamics Range
BM-6	Soviet Designation
BRL	Ballistics Research Laboratory
FAIR	Frankford Arsenal Interim Report
LFD	Launch & Flight Division
MR	Memorandum Report
SB	Silver Bullet
TR	Transonic Range
XM	Experimental Model

I. INTRODUCTION

Current developments in tank gunnery and in counterfire technology require increased emphasis on weapons systems of superior first hit/kill probability. Of critical importance in assessing the performance of such systems firing a particular projectile is the measure of dispersion, which is generally defined statistically to represent the radius of a target circle containing the hits of a group of rounds. Sources of dispersion include the gun mechanics, the interactions in the blast region between the projectile and the real environment, and the free flight aerodynamics.

A comprehensive statement of the aerodynamic contribution is presented by Murphy, Reference 1, to include the effects of spin, Magnus (side forces) and damping, and is identified as the aerodynamic jump. In those cases where these more subtle influences (spin, Magnus and damping) can be neglected, the simplified expression takes the form employed by Gallagher, Reference 2, which is restricted to application to symmetric missiles with essentially zero muzzle yaw. Predicting the magnitude of the aerodynamic jump requires an estimate of the initial yawing rate, usually available only from range tests, but it is clearly possible to calculate the remaining factors comprising the abbreviated aerodynamic jump term. This truncated coefficient constitutes a screening tool for the preliminary design survey, to be employed with discretion and directed to the elimination, on a rational basis, of unsuitable candidates from further consideration for manufacture or test.

This report compiles some locally available data and a corresponding calculation schedule for a selection of finned projectiles to demonstrate the premise. A length/mass normalizing unit is employed to illustrate comparability between even non-homologous design concepts.

II. PROCEDURE

For a given flight projectile subject to the constraints of symmetry and very low muzzle yaw, the simplified aerodynamic jump term[2] is given as:

$$J = \frac{I_y}{md^2} \frac{C_{L\alpha}}{C_{M\alpha}} \delta' = J_\zeta \delta' \qquad (1)$$

---

[1] *C.H. Murphy, "Free Flight Motion of Symmetric Missiles," BRL Report No. 1216, July 1963, (AD 442757).*

[2] *W.J. Gallagher, "Elements Which Have Contributed to Dispersion in the 90/40 mm Projectile,". BRL Report No. 1013, March 1957.* (AD #135306)

where I_y = transverse mass moment of inertia

m = mass

d = body diameter

$C_{L\alpha}$ = lift slope coefficient (at zero yaw)

$C_{M\alpha}$ = static moment slope coefficient (at zero yaw)

δ' = initial yawing rate

For the usual high length/diameter ratio fin-stabilized K.E. penetrator, the physical properties are reliably calculated and the initial yawing rate postulated by limit, but there is little test data available indicating the static aerodynamic coefficients C_D, $C_{M\alpha}$ and $C_{L\alpha}$, the drag, static moment and lift force coefficients, respectively. A calculating technique, described in Reference 3, is therefore applied using several prototype projectile configurations.

Reference 3 requires the physical properties and the geometry, including the fin planform, to be specified. A tabular computing scheme, based on modified empirical data, fixes the separate normal force slope coefficients with fin-body interference effects included. From the component normal forces and a determination of the center of pressure[3], the resolved moment is obtained. By independent calculation (or range determination) of the drag coefficient[4] the lift slope coefficient is established. A final form of the aerodynamic jump factor is then formulated. This factor, J_ζ, is discussed in the parametric analysis in Appendix A.

III. RESULTS

Figures 1 thru 12 summarize the complete results of this preliminary survey. An outline drawing, in caliber dimensions, is accompanied on the facing page by a reference table listing the physical properties and selected curves plotting the static aerodynamic characteristics and aerodynamic jump factors for the Mach range from 2 to 5. The solid line on the graphs is determined using calculated values of C_D, $C_{L\alpha}$ and $C_{M\alpha}$. Data points, where shown, rely on measured values of $C_{L\alpha}$ and $C_{M\alpha}$ as available. The physical properties are given in both specified dimensions

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[3] *AMCP 706-280, "Design of Aerodynamically Stabilized Free Rockets," 1968.*

[4] *W.F. Donovan and B.B. Grollman "Procedure for Estimating Zero Yaw Drag Coefficients for Long Rod Projectiles at Mach Numbers from 2 to 5," ARBRL MR 02819, March 1978.*

and in normalized caliber notation. Such a device (normalizing) converts the projectile to uniform monolithic construction of dynamic properties associated with the physical model. Appendix B contains a short description of the normalizing technique. It appears that the calculating procedure can determine the total normal force and static moment coefficients within 20% of those known values corresponding to zero yaw conditions, and that additional interpolation between charts can reduce this spread. A separate investigation is being conducted into the comparative features of a similar procedure using the same basic data which can be programmed for computer analysis[5].

Appendix C presents a nomograph of the equation

$$J_\zeta = \frac{I_y}{md^2} \; \frac{C_{L\alpha}}{C_{M\alpha}} \tag{2}$$

where the range of variables can be readily identified. The normal force slope coefficient, rather than the lift slope coefficient, is often available and the conversion follows from the branch axis which performs the subtraction

$C_{L\alpha} = C_{N\alpha} - C_D$ where $C_{N\alpha}$ = normal force slope coefficient and C_D = drag coefficient.

Normalized units are employed for generality.

Figure 1 shows a current design projectile which has the highest length/diameter configuration examined. The penetrator driving grooves are not shown nor is any aerodynamic consideration given to the grooves in the calculations.

Figure 2 describes the standard flechette. The calculations are based on a hypothetical straight sweep fin instead of the reflex curvature actually employed. The boattail at the base of the fin was not included in the aerodynamics on the basis that the manufacture in this region was rather crude.

Figures 3 and 4 present a previous design projectile which carries a bulbous nose and a fin hub of greater diameter than the central body portion. Again, no allowance was made for the driving grooves. The caliber reference is to the largest diameter of the windshield. Two fin sweepback angles were investigated.

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[5] *W.D. Washington, "Computer Program, for Estimating Stability Derivatives of Missile Configurations," U.S. Army Missile Command Report RD7625, May 1976.*

Figure 5 is an outline of a blunted nose flechette. This projectile represents a different approximation in that calculating procedures for the normal force slope coefficient are not within the scope of the present scheme and are not firmly established by even more elaborate techniques[6]. The normal force of the forebody is taken as zero. The total drag coefficient (from test data, Reference 6) has a characteristic rising value well into the supersonic region and in combination with the calculated fin coefficients allows a calculation of the overall body static aerodynamics. The results are low in value when compared to test data.

Figure 6 shows a current domestic technology effort produced by a commercial firm.

Figure 7 portrays a BRL design proposed for incorporation into an advanced program.

Figure 8 considers a foreign technology penetrator. The forebody was taken as the sum of a cone-cylinder-flare and a hypothetical long boattail interrupted by a short cylindrical section. The intermediate cylinder, which carries the driving grooves, is not assigned any normal force. This fin is six-bladed.

Figure 9 represents an early version of a domestic technology projectile. The fielded design has been modified and employs a completely different fin.

Figures 10 and 11 show the XM-579/8 series projectile, and two grossly different fins have been tested. The small fin profile was not entered into production.

Figure 12 describes an experimental design on which careful aerodynamic studies were conducted in the Edgewood Area Wind Tunnel facility.

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[6] *L.C. MacAllister, "Drag and Stability Properties of the XM144 Flechette with Various Head Shapes," BRL MR No. 1981, May 1969.* (AD #854724)

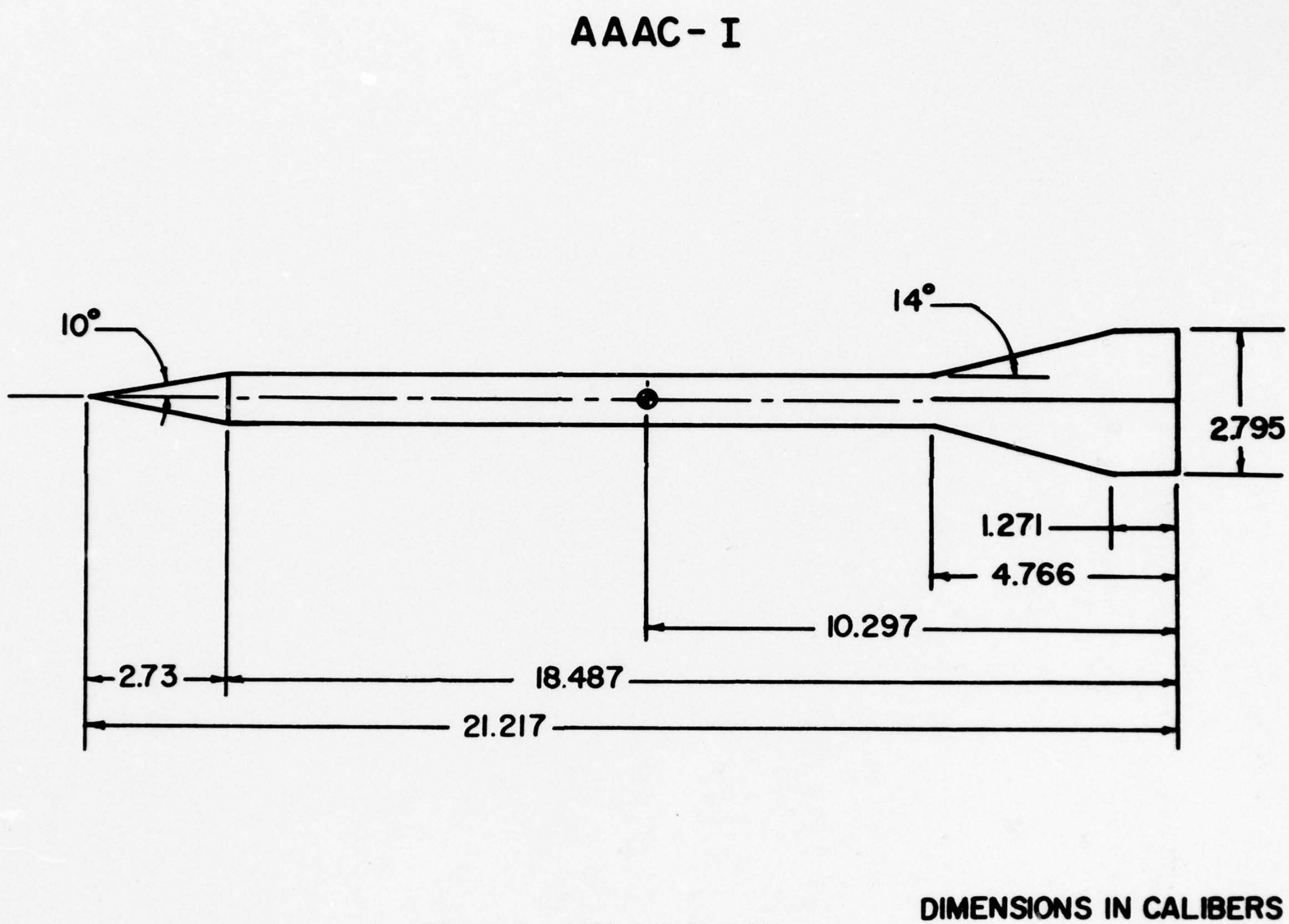


Figure 1. AAAC-I Projectile

AAAC - I

PHYSICAL PROPERTIES		
	SPECIFIED	NORMALIZED
m	3.92 lb	222.7 cal^3
I_x	.273 lb in^2	25.04 cal^5
I_y	60.37 lb in^2	5537.7 cal^5
d	.787 in	1.0 cal
$\frac{I_y}{md^2}$	24.87	24.87
REFERENCE : CALCULATED		

+ PRELIMINARY DATA (LFD, BRL)

— EQ. (2)

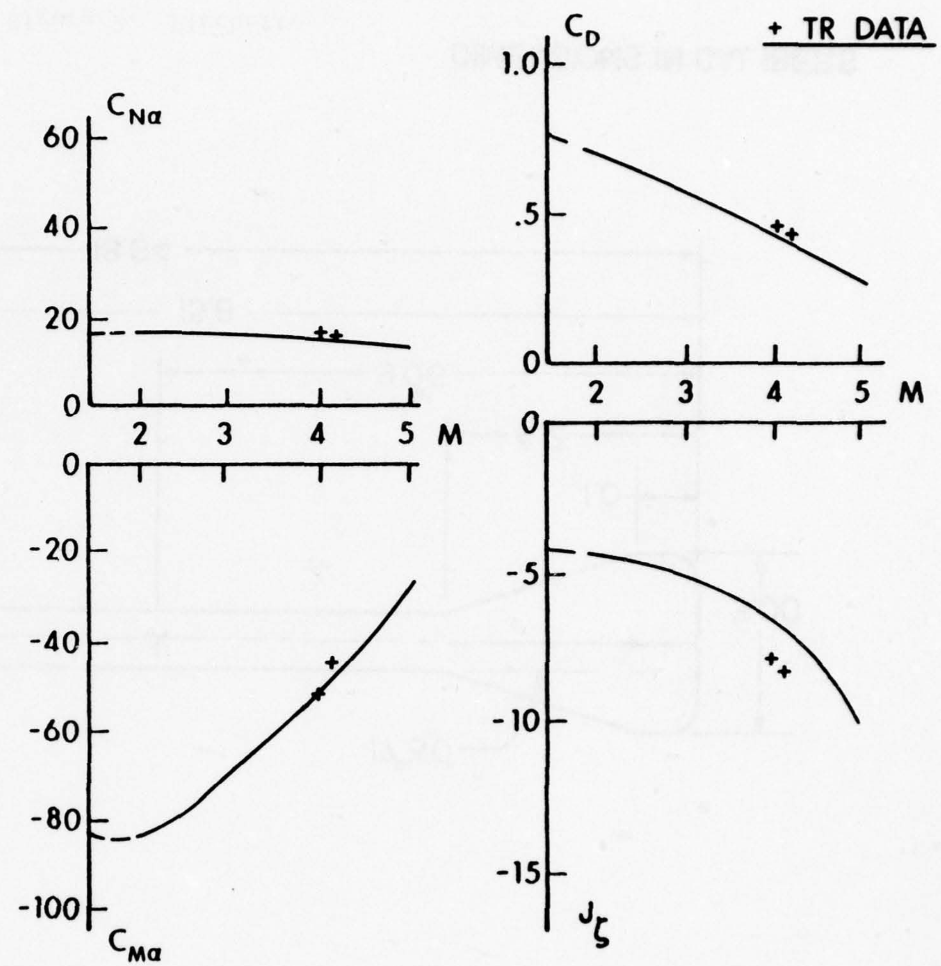
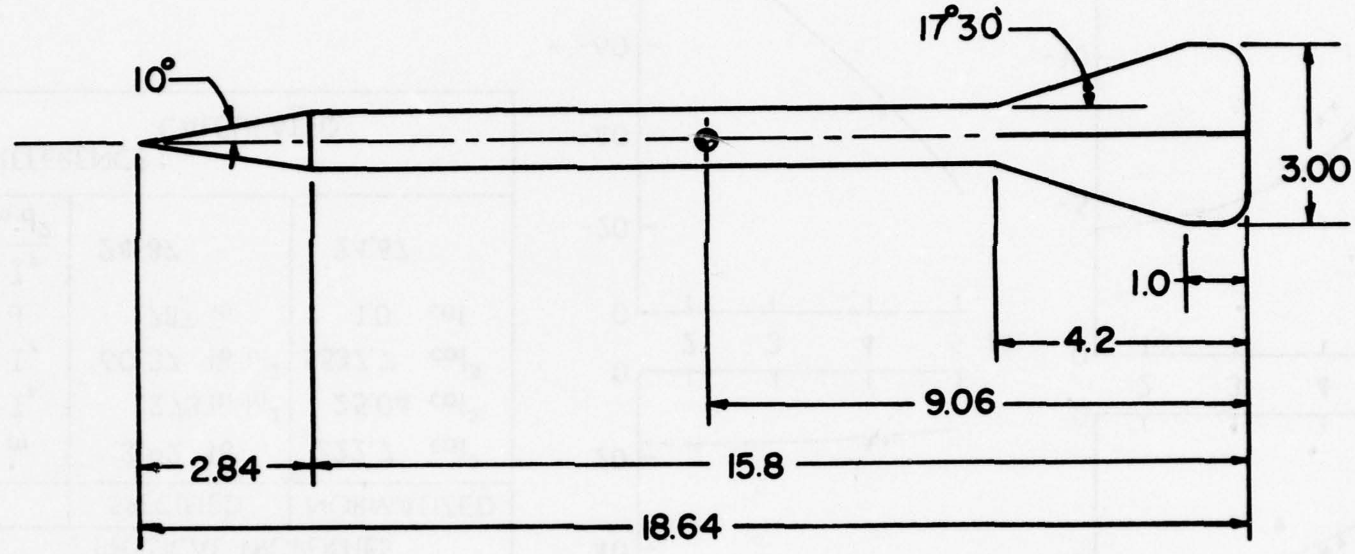


Figure 1A Physical Properties AAAC-I Projectile

FLECHETTE



DIMENSIONS IN CALIBERS

Figure 2. Flechette

FLECHETTE (RD. FINS)

	PHYSICAL PROPERTIES	
	SPECIFIED	NORMALIZED
m	.525 g	91.43 cal^3
I_x	~	~ cal^5
I_y	.359 g cm^2	1949.76 cal^5
d	.0705 in	1.0 cal
$\frac{I_y}{m d^2}$	21.33	21.33
REFERENCE: BRL MR 1981		

+ MR 1981

— EQ. (2)

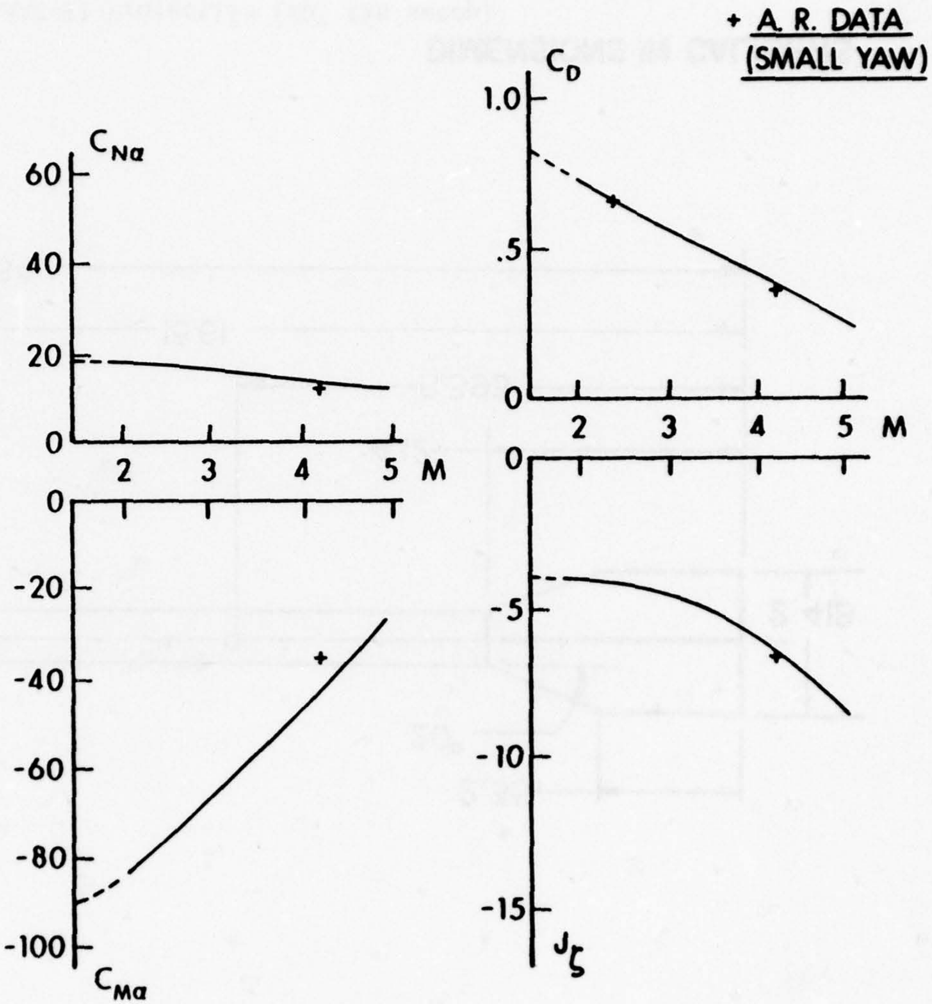


Figure 2A Physical Properties Flechette

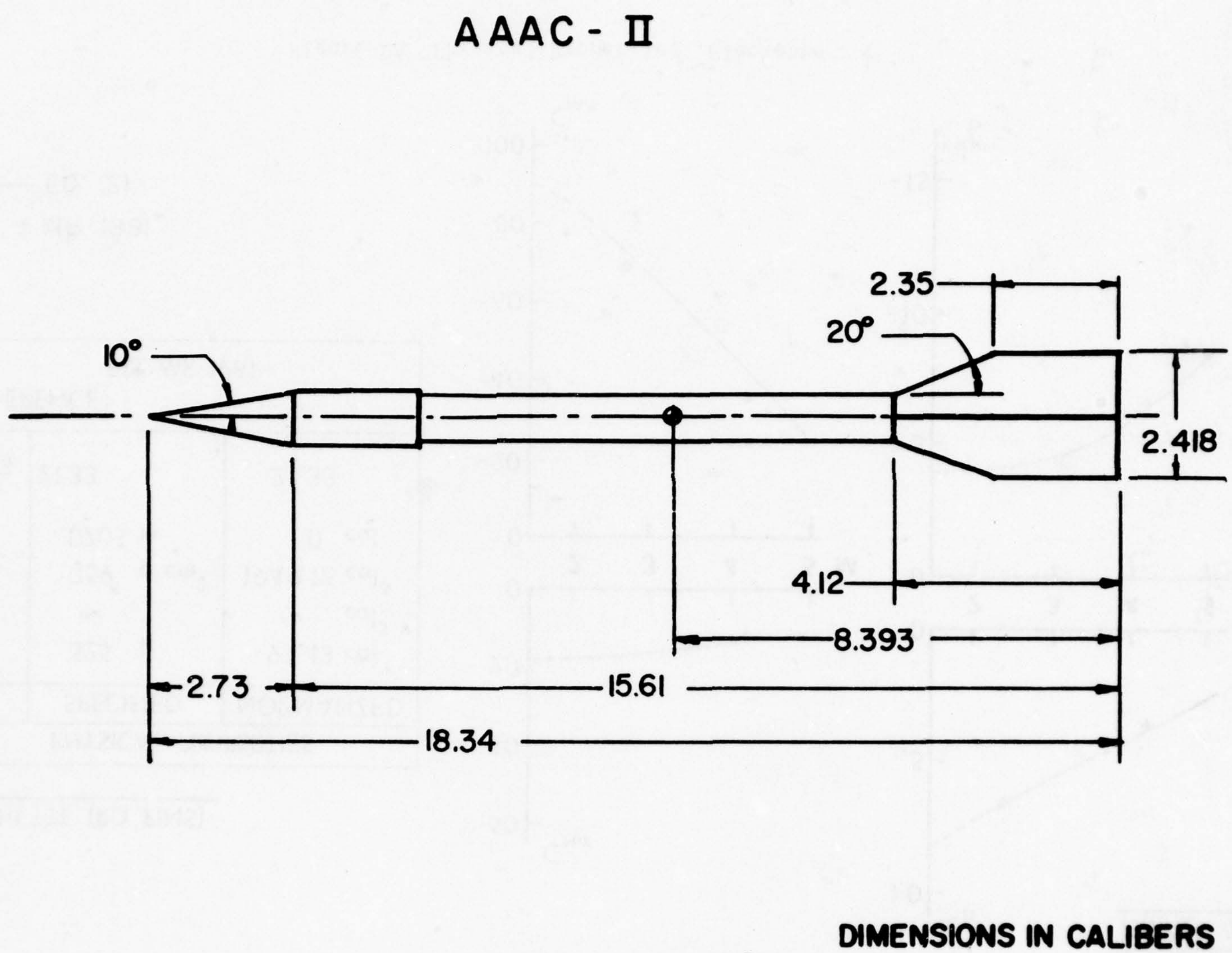


Figure 3. AAAC-II Projectile (20° fin sweep)

AAAC - II (20°)

PHYSICAL PROPERTIES		
	SPECIFIED	NORMALIZED
m	4.19 lb	153.97 cal^3
I_x	.345 lb in^2	44.37 cal^5
I_y	67.10 lb in^2	2977.66 cal^5
d	.91 in	1.0 cal
$\frac{I_y}{m d^2}$	19.34	19.34
REFERENCE : CALCULATED		

+ PRELIMINARY DATA (LFD, BRL)

— EQ. (2)

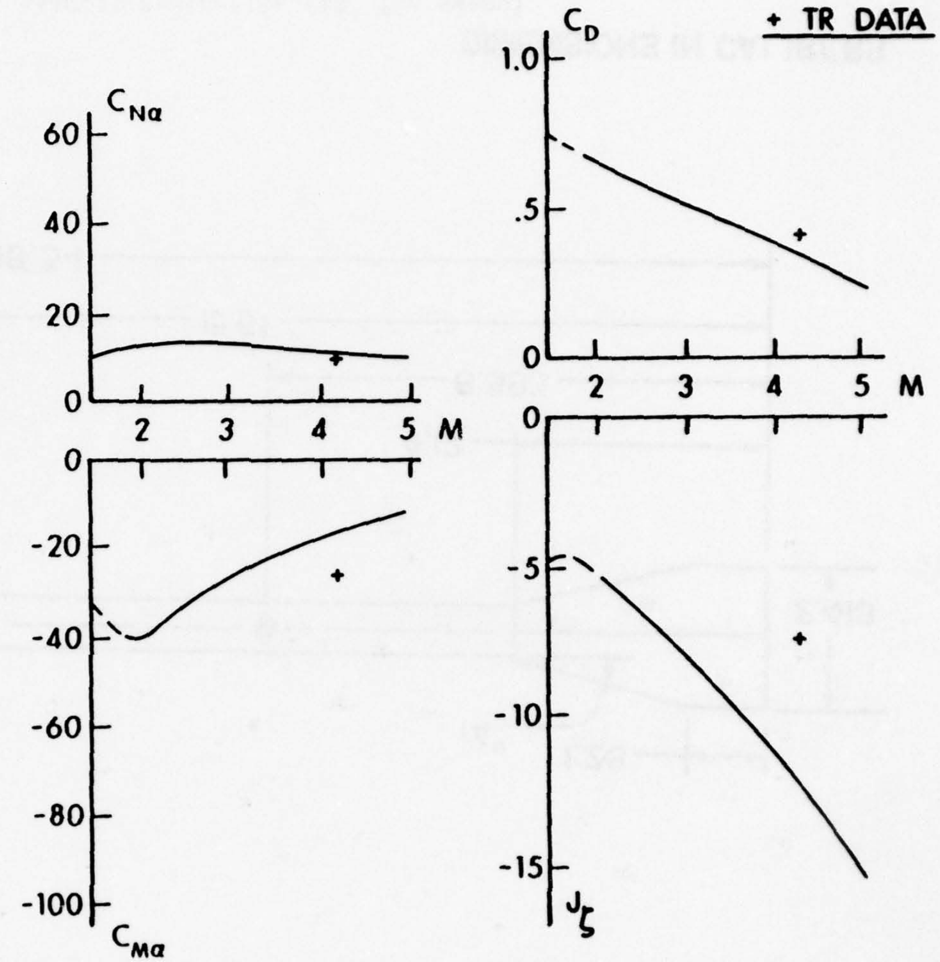


Figure 3A Physical Properties AAAC-II Projectile 20°Fin Sweep

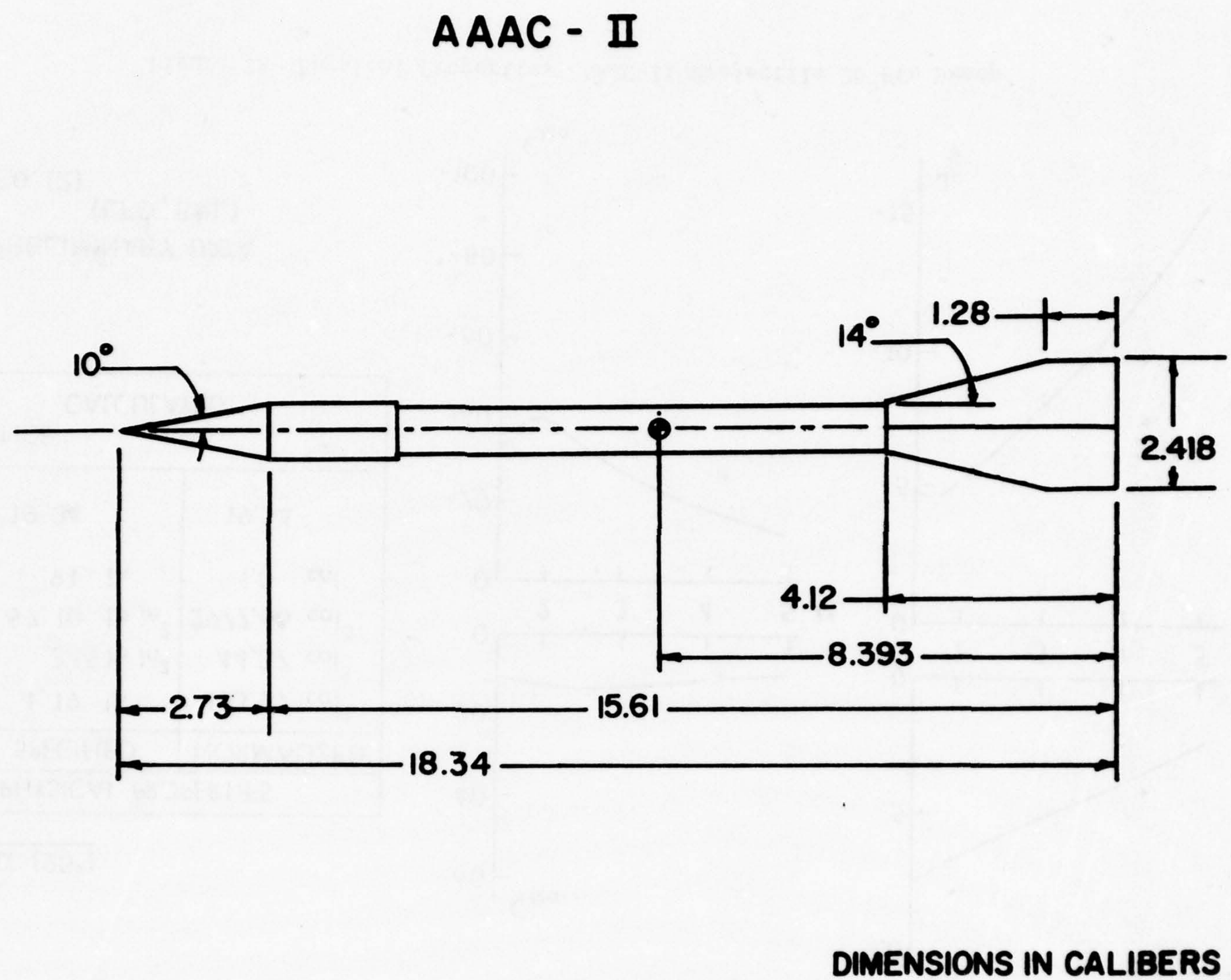


Figure 4. AAAC-II Projectile (14° fin sweep)

AAAC - II (14°)

	PHYSICAL PROPERTIES	
	SPECIFIED	NORMALIZED
m	4.17 lb	153.97 cal^3
I_x	.345 lb in^2	55.31 cal^5
I_y	67.09 lb in^2	2977.21 cal^5
d	.91 in	1.0 cal
$\frac{I_y}{md^2}$	19.34	19.34
REFERENCE : T. R. MEASURED		

+ PRELIMINARY DATA (LFD, BRL)

— EQ. (2)

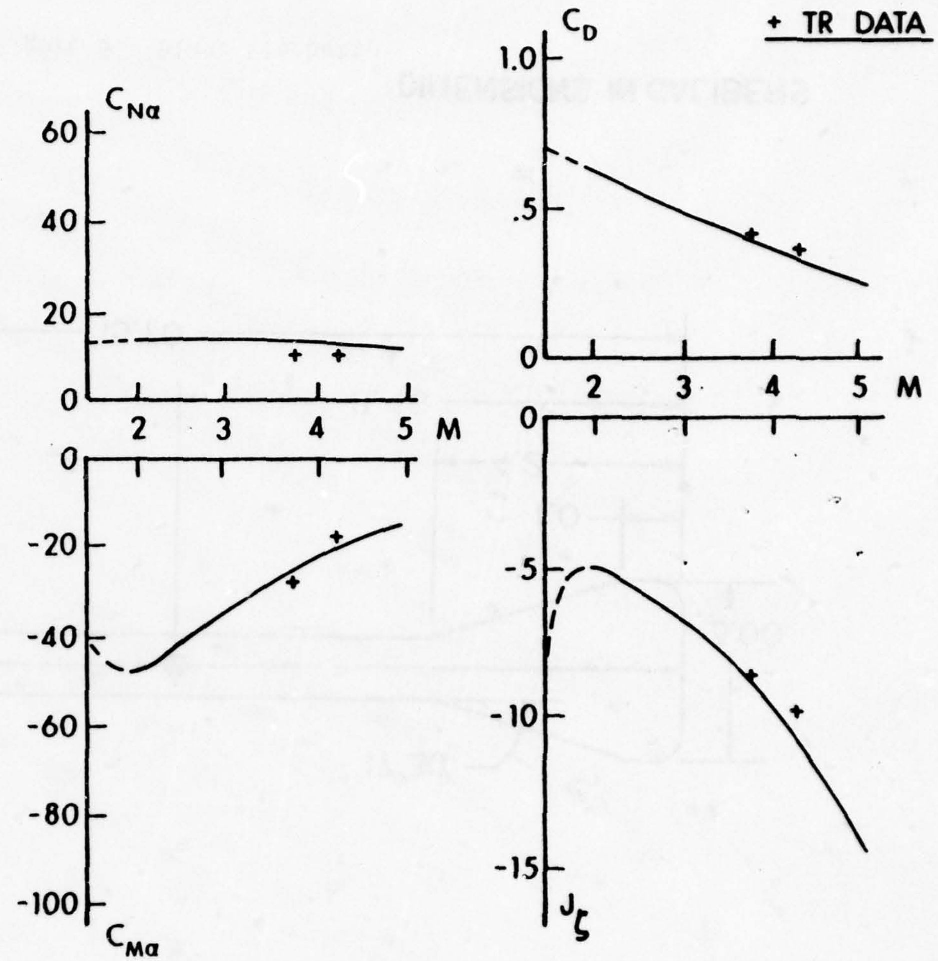


Figure 4A Physical Properties AAAC-II Projectile 14°Fin Sweep

BLUNT FLECHETTE

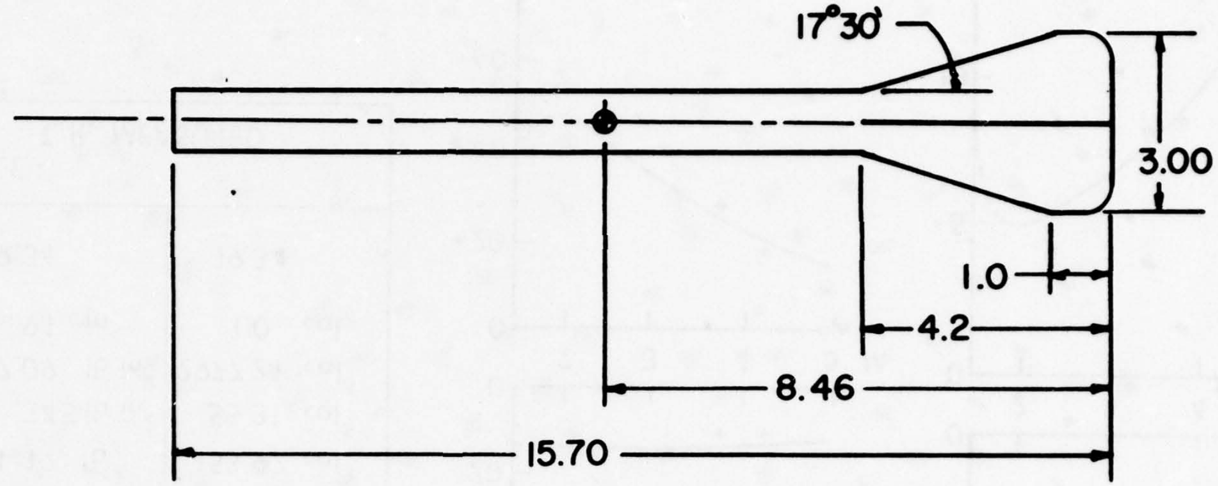


Figure 5. Blunt Flechette

FLECHETTE (BLUNT NOSE, RD. FINS)

	PHYSICAL PROPERTIES	
	SPECIFIED	NORMALIZED
m	.495 g	86.21 cal^3
I_x	~	~ cal^5
I_y	.297 g cm^2	1613.03 cal^5
d	.0705 in	1.0 cal
$\frac{I_y}{m d^2}$	18.71	18.71
REFERENCE: BRL MR 1981		

—+-+—+ MR 1981

—— EQ. (2)

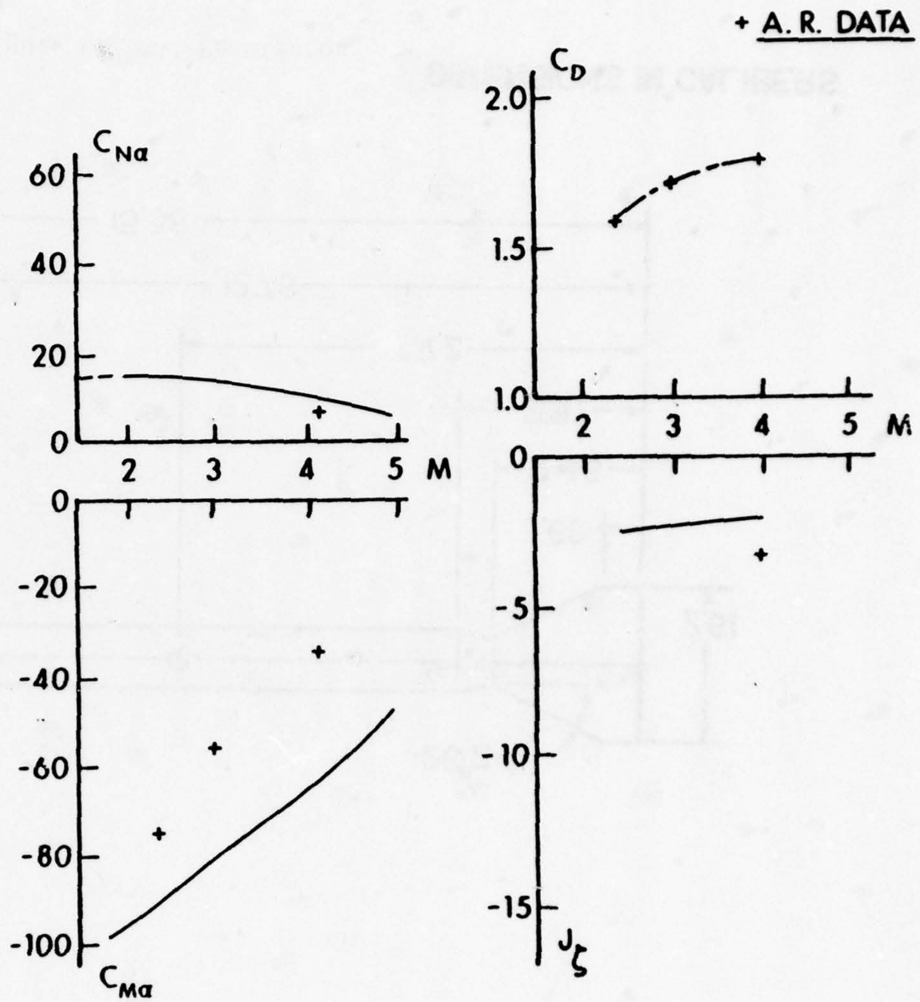


Figure 5A Physical Properties Blunt Flechette

AAI

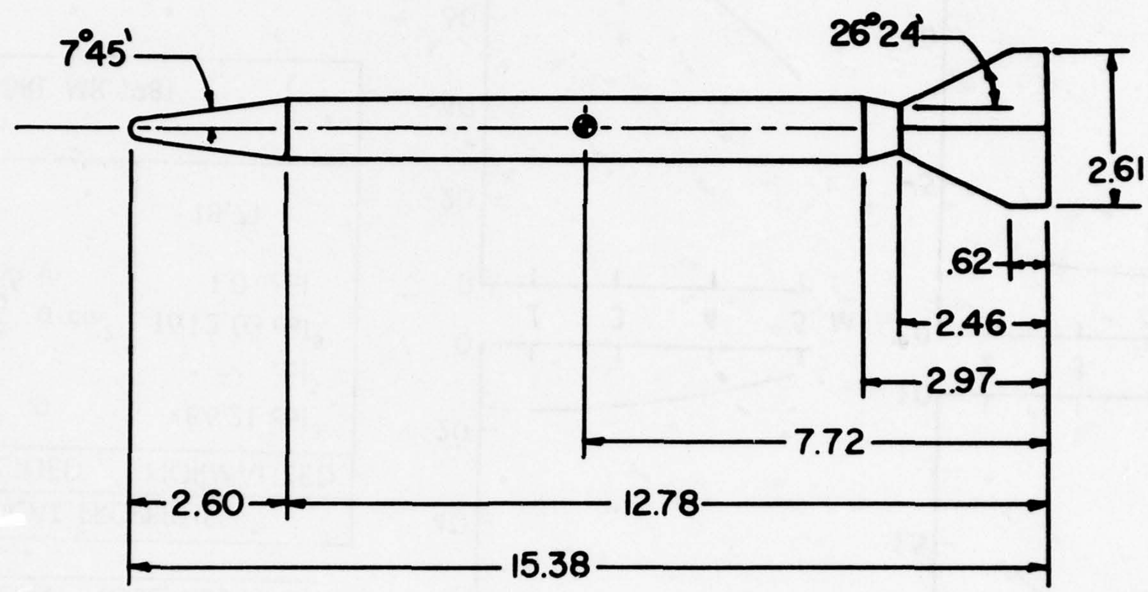


Figure 6. AAI Penetrator

DIMENSIONS IN CALIBERS

AAI

PHYSICAL PROPERTIES		
	SPECIFIED	NORMALIZED
m	1.38 kg	157.86 cal³
I_x	.068 g m²	cal⁵
I_y	8.40 g m²	2264.35 cal⁵
d	.0206 m	1.0 cal
$\frac{I_y}{m d^2}$	14.34	14.34
REFERENCE: T. R. MEASURED		

+ PRELIMINARY DATA (LFD, BRL)

— EQ. (2)

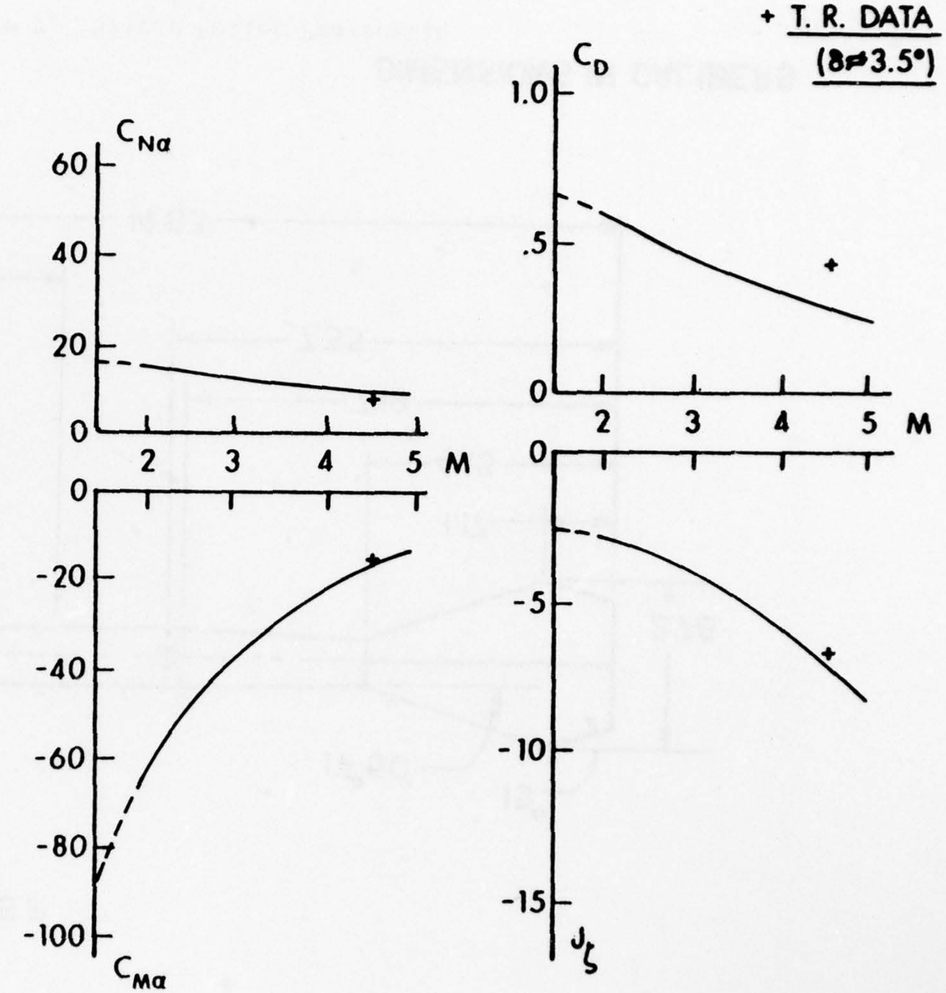


Figure 6A Physical Properties AAI Penetrator

SILVER BULLET

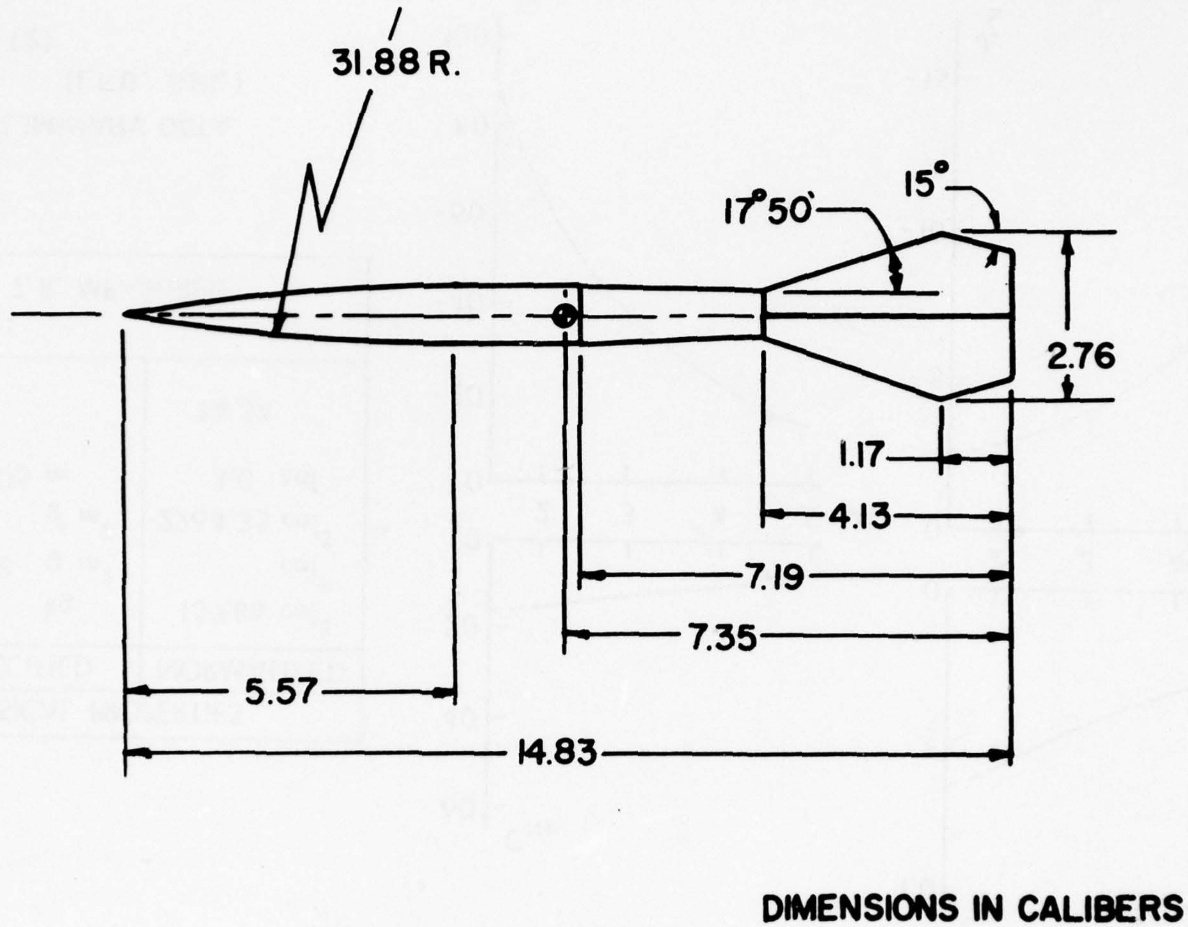


Figure 7. Silver Bullet Projectile

S. B.

PHYSICAL PROPERTIES		
	SPECIFIED	NORMALIZED
m	4.2 kg	97.46 cal^3
I_x	7.31 kg cm^2	13.92 cal^5
I_y	534.5 kg cm^2	1017.67 cal^5
d	3.5 cm	1.0 cal
$\frac{I_y}{md^2}$	10.39	10.39
REFERENCE: T. R. MEASURED		

+ PRELIMINARY DATA (EBL, BRL)

— EQ. (2)

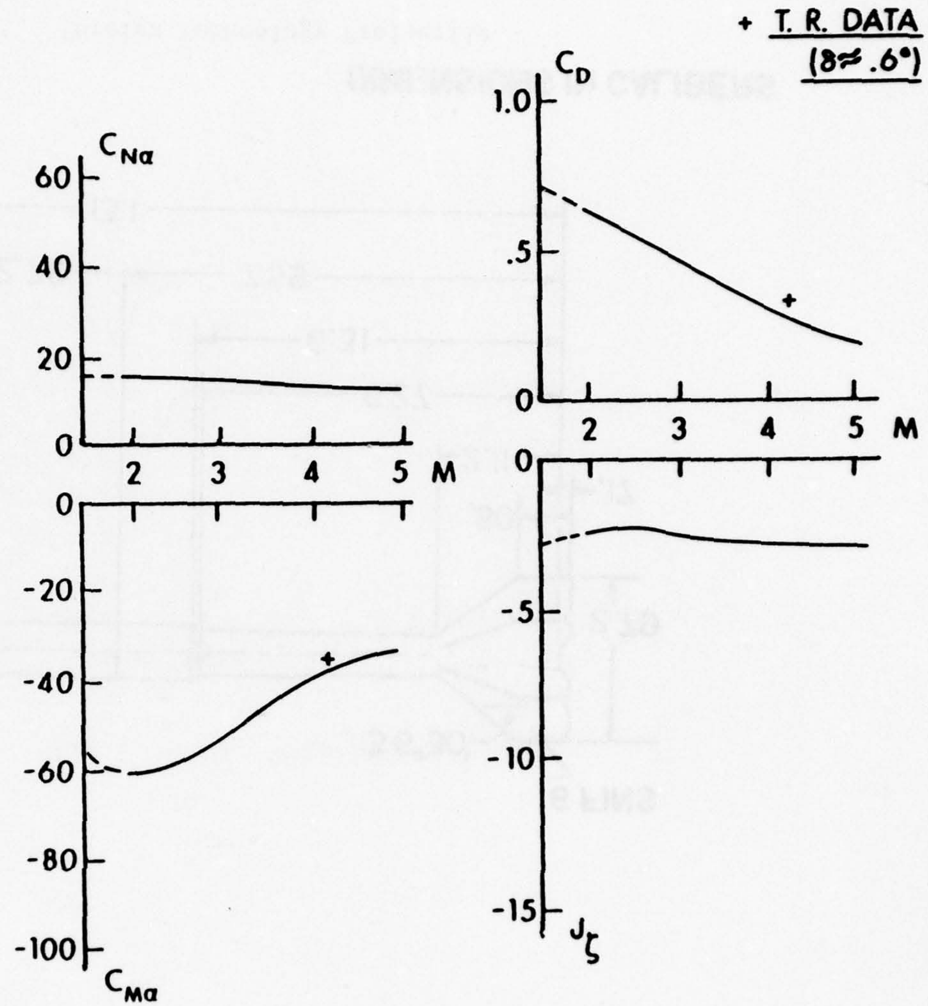


Figure 7A Physical Properties Silver Bullet Projectile

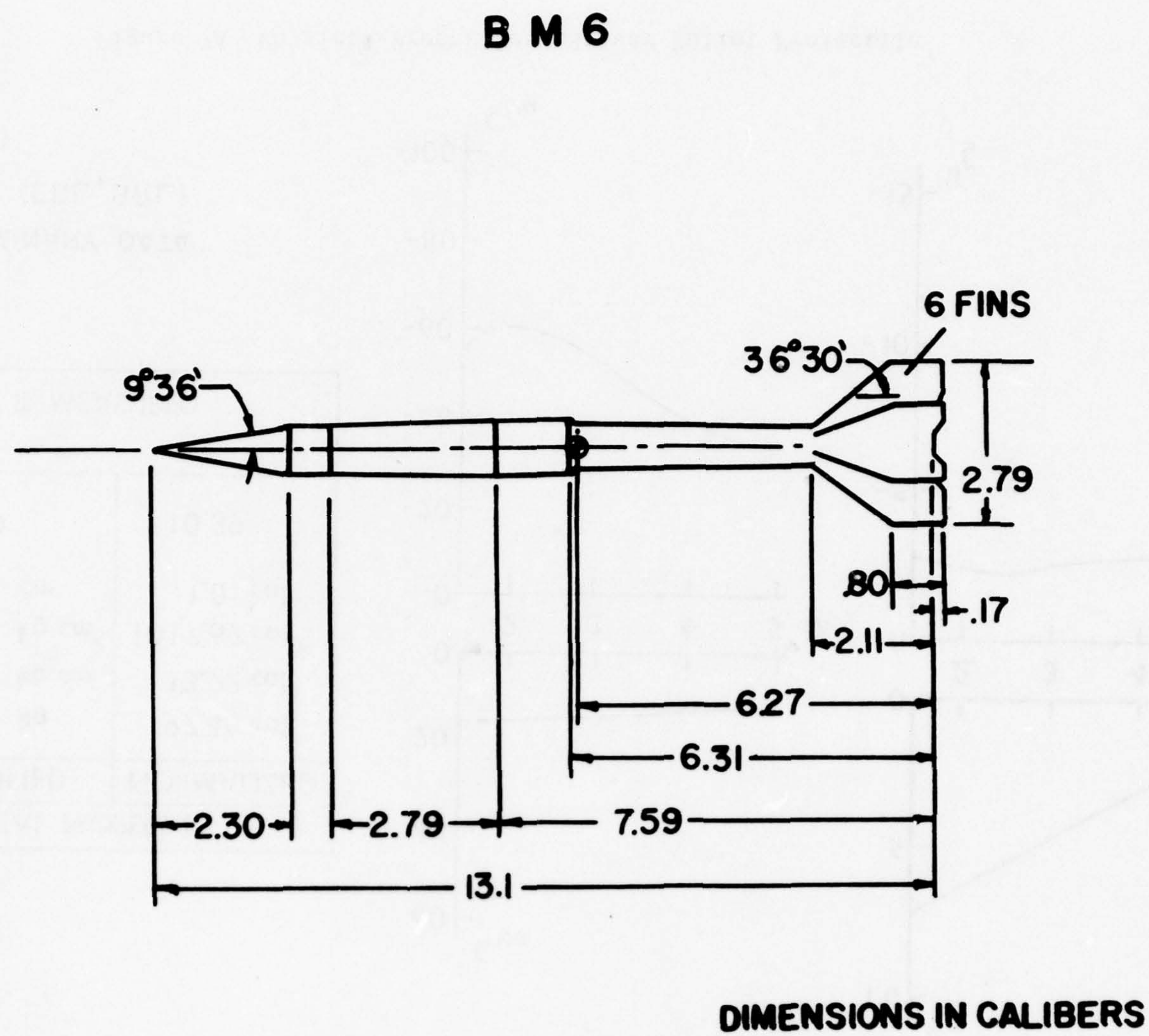


Figure 8. Foreign Technology Projectile

BM 6

PHYSICAL PROPERTIES		
	SPECIFIED	NORMALIZED
m	8.50 lb	53.36 cal^3
I_x	3.59 lb in^2	8.38 cal^5
I_y	277.10 lb in^2	646.81 cal^5
d	1.64 in	1.0 cal
$\frac{I_y}{m d^2}$	12.12	12.12
REFERENCE : CALCULATED		

EQ. (2)

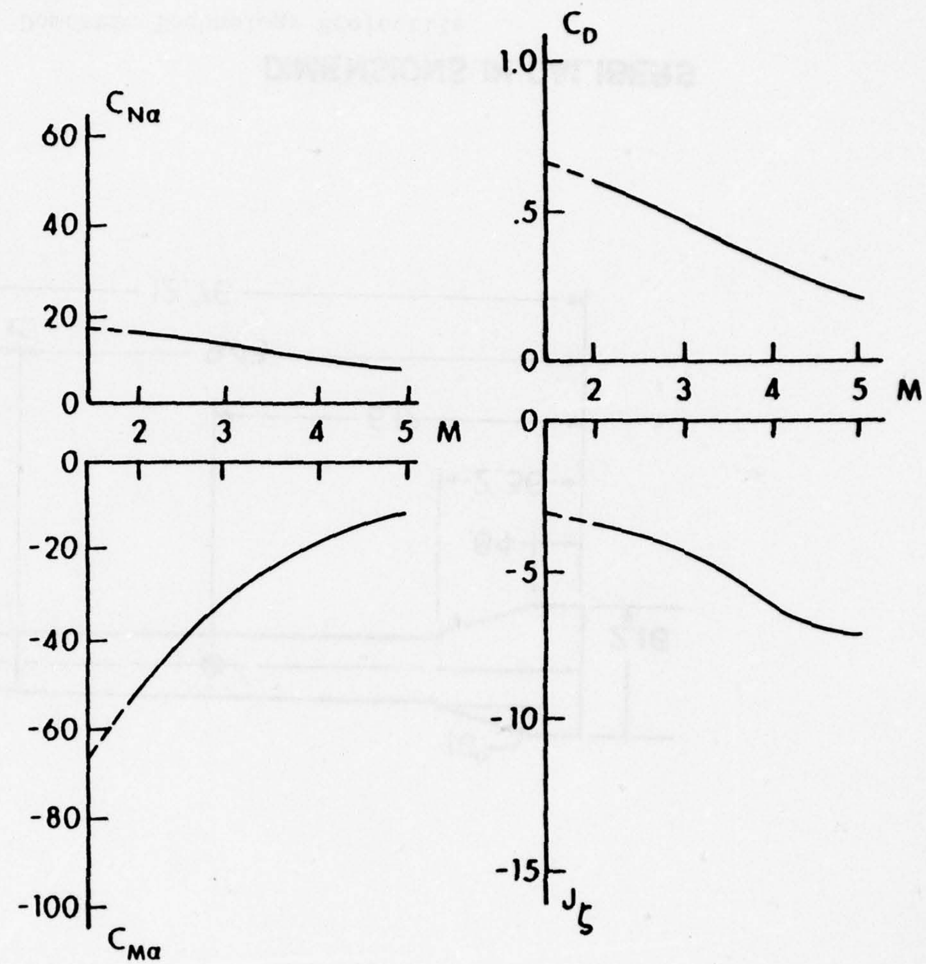


Figure 8A Physical Properties Foreign Technology Projectile

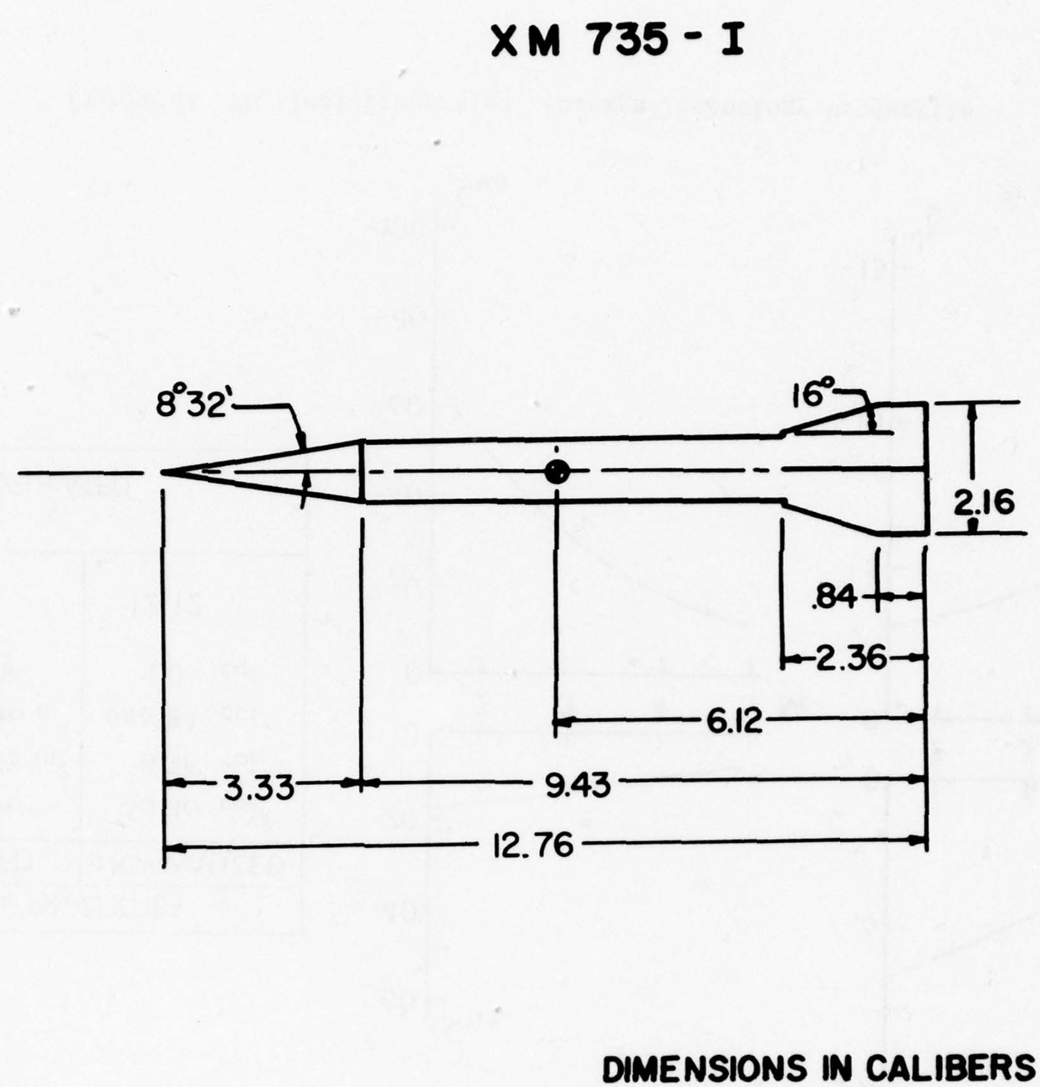


Figure 9. Domestic Technology Projectile

XM735-I

PHYSICAL PROPERTIES		
	SPECIFIED	NORMALIZED
m	8.15 lb	84.03 cal^3
I_x	1.56 lb in^2	8.32 cal^5
I_y	121.54 lb in^2	648.64 cal^5
d	1.39 in	1.0 cal
$\frac{I_y}{m d^2}$	7.72	7.72
REFERENCE: CALCULATED		

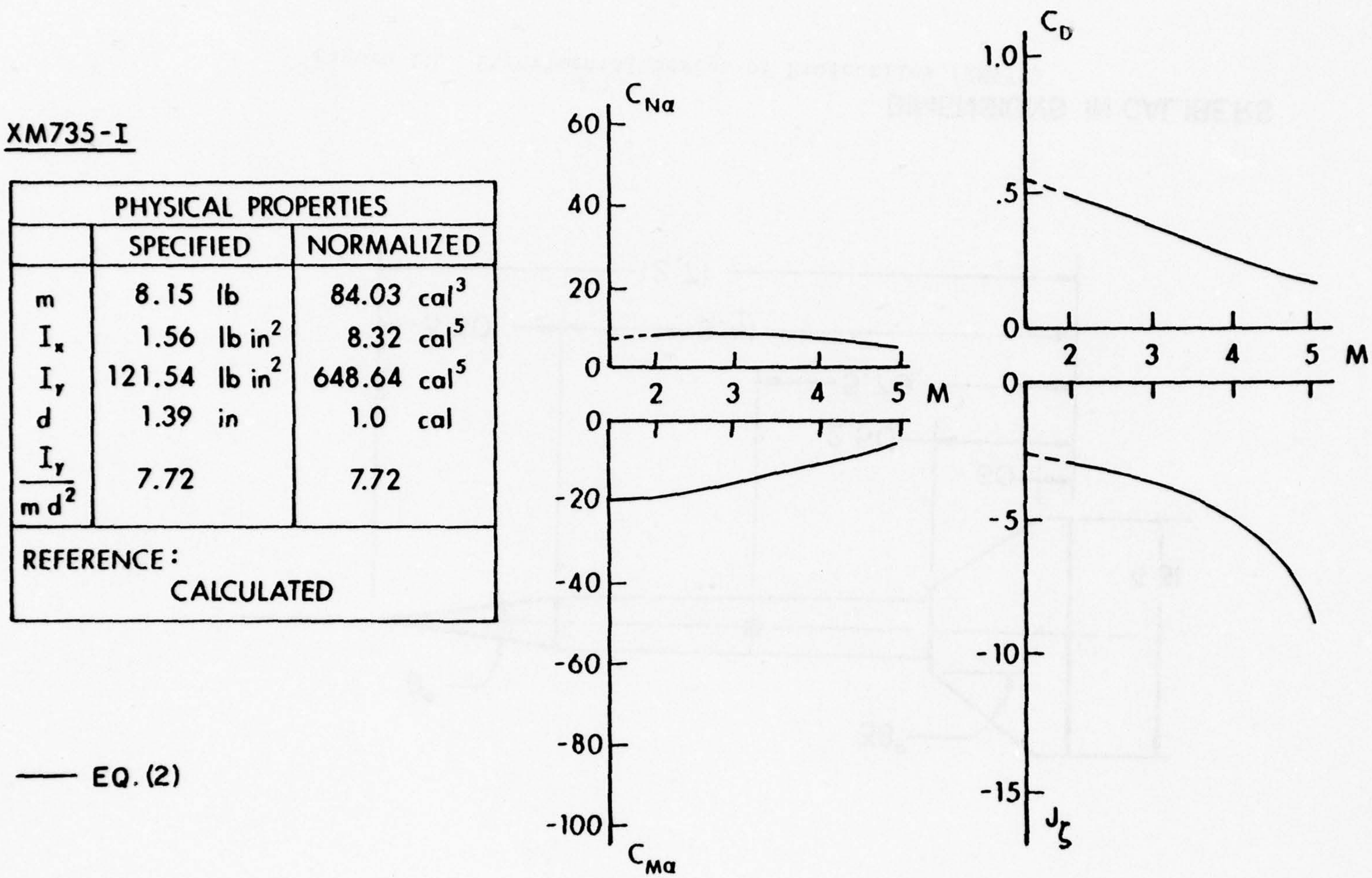
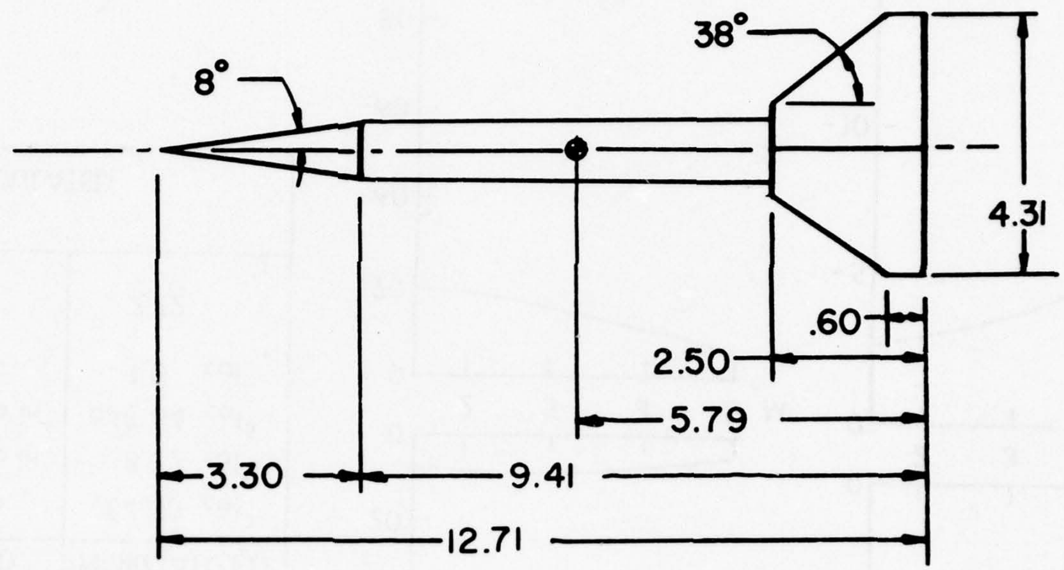


Figure 9A Physical Properties Domestic Technology Projectile

XM 579



DIMENSIONS IN CALIBERS

Figure 10. Experimental Series of Projectiles (XM579)

XM579E-4

PHYSICAL PROPERTIES		
	SPECIFIED	NORMALIZED
m	8.31 lb	85.69 cal^3
I_x	3.61 lb in^2	19.27 cal^5
I_y	145.0 lb in^2	773.84 cal^5
d	1.39 in	1.0 cal
$\frac{I_y}{md^2}$	9.03	9.03
REFERENCE : T. R. MEASURED		

+ PRELIMINARY DATA (EBL, BRL)

— EQ. (2)

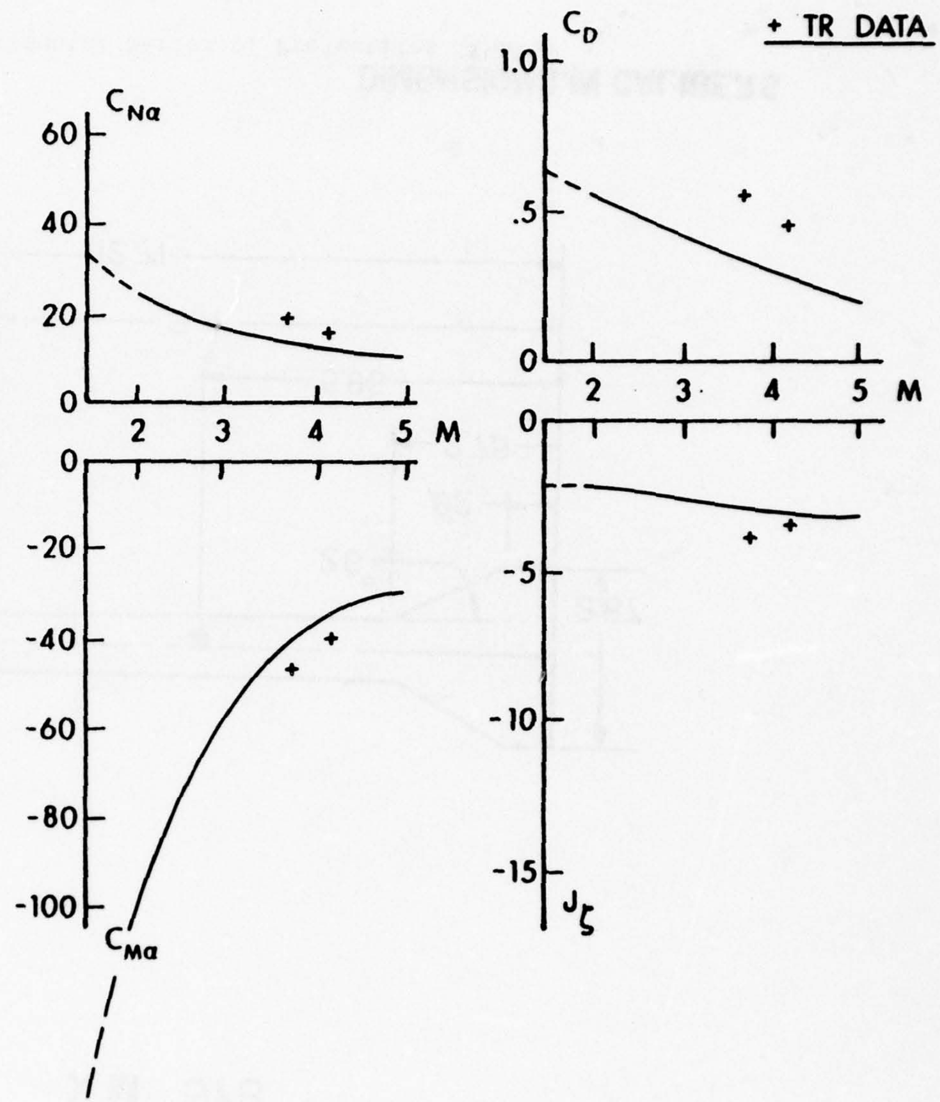
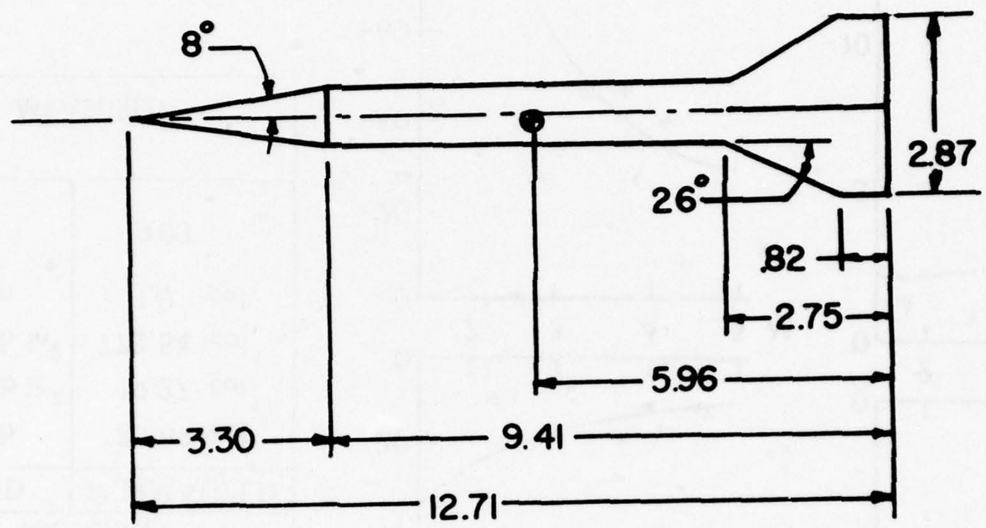


Figure 10A Physical Properties XM579

XM 578



DIMENSIONS IN CALIBERS

Figure 11. Experimental Series of Projectiles (XM578)

XM578

PHYSICAL PROPERTIES		
	SPECIFIED	NORMALIZED
m	7.89 lb	81.36 cal^3
I_x	1.70 lb in^2	9.08 cal^5
I_y	121.43 lb in^2	648.05 cal^5
d	1.39 in	1.0 cal
$\frac{I_y}{m d^2}$	7.97	7.97
REFERENCE : T. R. MEASURED		

+ PRELIMINARY DATA (EBL, BRL)

— EQ. (2)

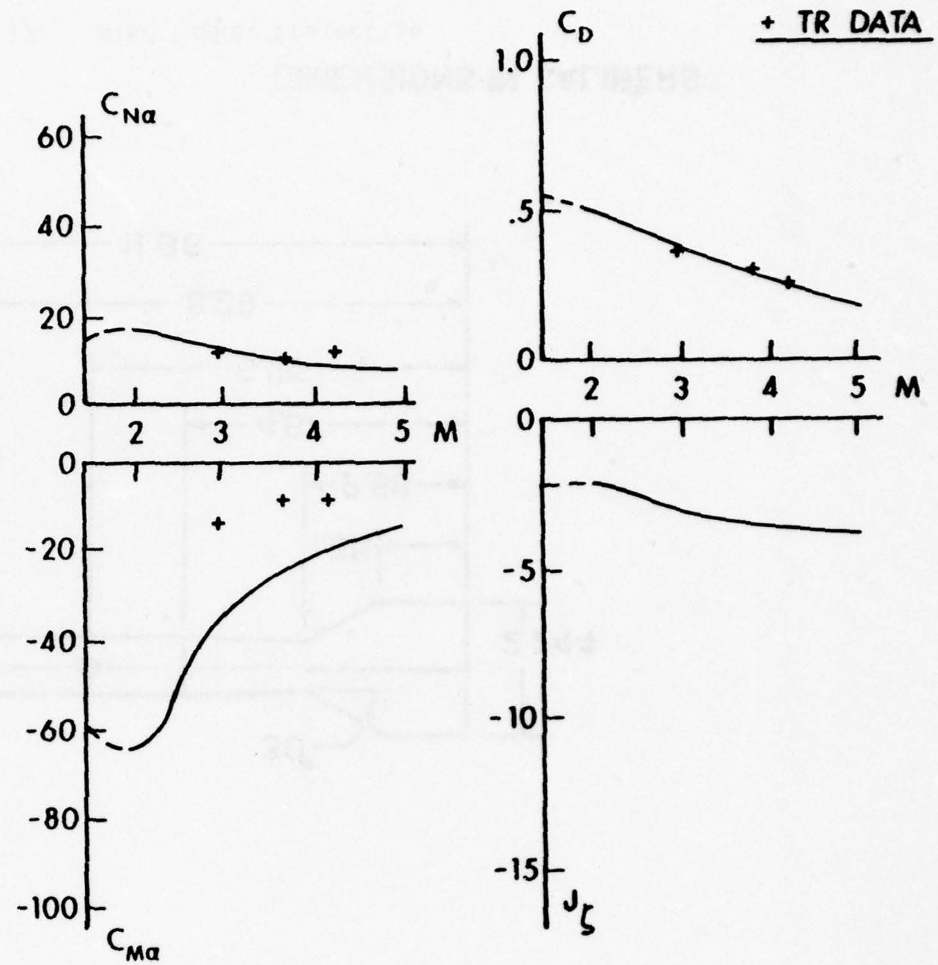
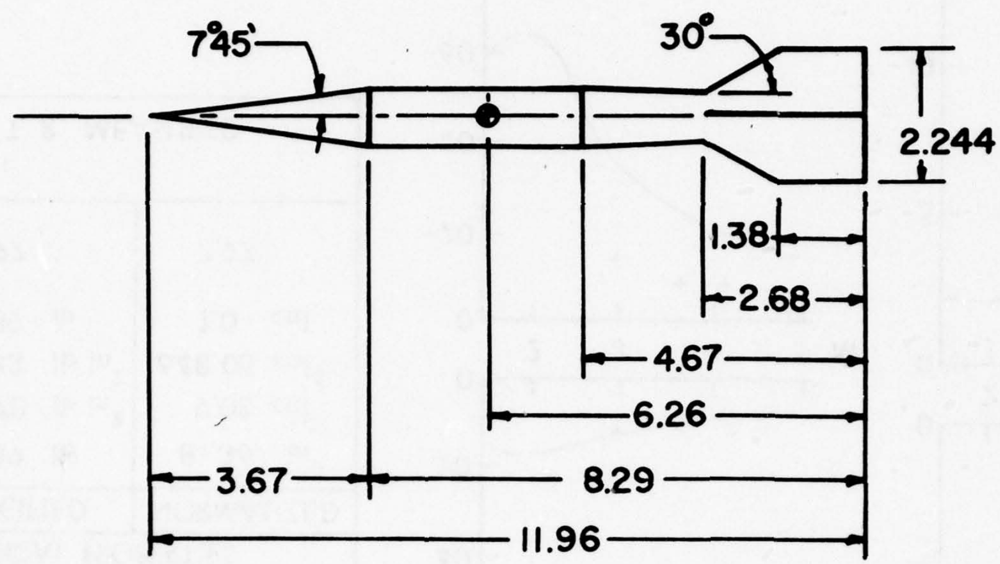


Figure 11A Physical Properties XM578

FRANKFORD-EDGEWOOD



DIMENSIONS IN CALIBERS

Figure 17. Wind Tunnel Projectile

FRANKFORD/EDGEWOOD

	PHYSICAL PROPERTIES	
	SPECIFIED	NORMALIZED
m	.304 lb	58.30 cal^3
I_x	.0193 lb in^2	13.53 cal^5
I_y	.570 lb in^2	399.56 cal^5
d	.524 in	1.0 cal
$\frac{I_y}{m d^2}$	6.83	6.83
REFERENCE : FAIR 13-MDC-A-76		

+ FAIR 13-MDC-A-76

— EQ. (2)

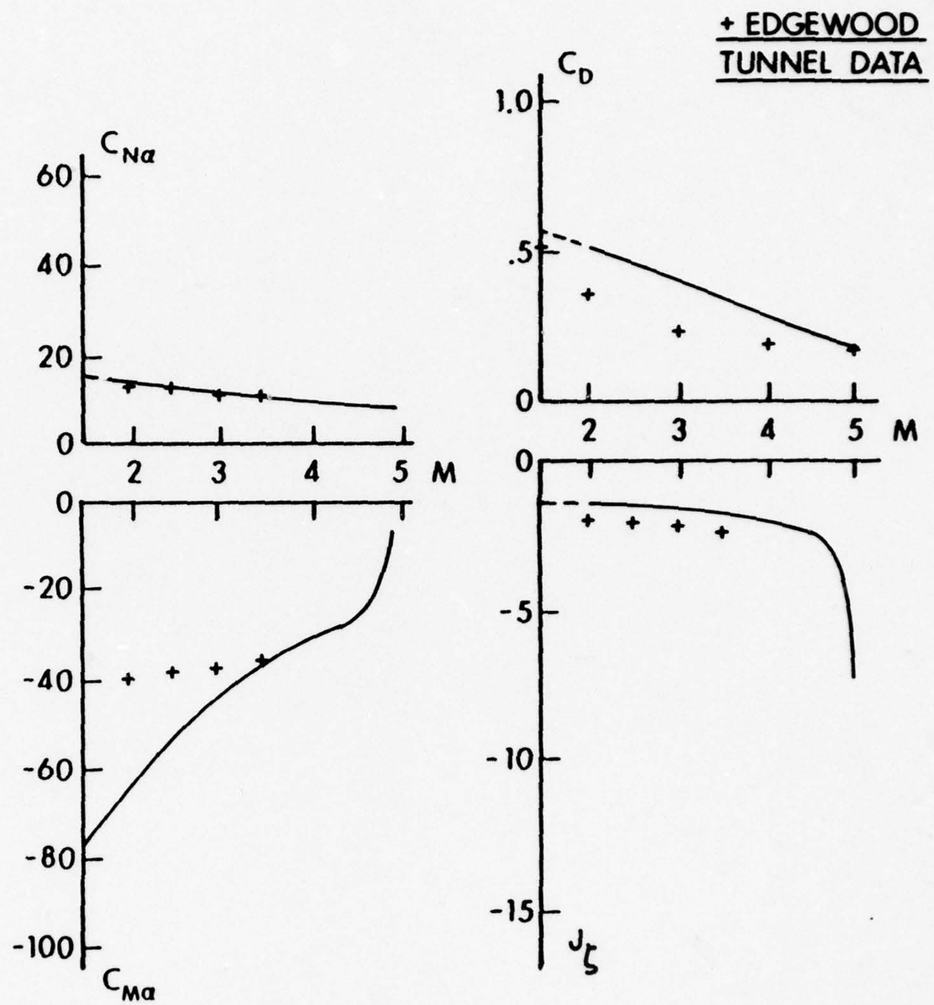


Figure 12A Physical Properties Wind Tunnel Projectile

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1. C. H. Murphy, "Free Flight Motion of Symmetric Missiles," BRL Report No. 1216, July 1963, (AD #442757).

2. W. J. Gallagher, "Elements Which Have Contributed to Dispersion in the 90/40mm Projectile," BRL Report No. 1013, March 1957. (AD #135306)

3. AMCP 706-280, "Design of Aerodynamically Stabilized Free Rockets," 1968.

4. W. F. Donovan and B. B. Grollman, "Procedure for Estimating Zero Yaw Drag Coefficients for Long Rod Projectiles at Mach Numbers from 2 to 5," ARBRL MR02819, March 1978.

5. W. D. Washington, "Computer Program for Estimating Stability Derivatives of Missile Configurations," U. S. Army Missile Command Report RD-76-25, May 1976.

6. L. C. MacAllister, "Drag and Stability Properties of the XM144 Flechette with Various Head Shapes," BRLMR No. 1981, May 1969. (AD #854724)

APPENDIX A

PARAMETRIC EXAMINATION OF ACCURACY FACTOR

From the aerodynamic jump "accuracy factor"

$$J_\zeta = \frac{I_y}{md^2}\ \frac{C_{L\alpha}}{C_{M\alpha}}$$

$$\doteq \frac{I_y}{md^2}\ \frac{C_{N\alpha}}{C_{M\alpha}}$$

where $C_{N\alpha} = C_{L\alpha} + C_D$ and $C_D << C_{N\alpha}$

$$J_\zeta = f\left(\frac{C_{N\alpha}}{C_{M\alpha}}\right)$$

The effect of fin performance on the aerodynamic jump can be examined under the assumptions of singular non-coupling variables and essentially zero-yaw behavior.

Figure A-1 defines the projectile geometry

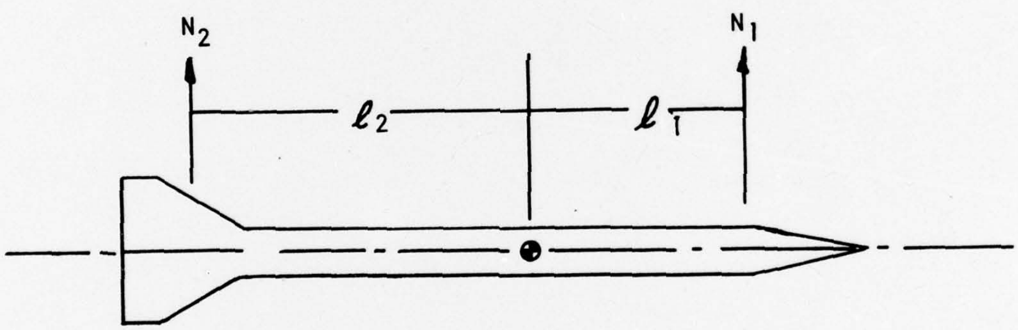

Figure A-1 Representative Projectile

N_1 = Normal force due to nose-forebody lift.

N_2 = Normal force due to fin lift.

ℓ_1 = Distance from c.g. to forebody center of force

ℓ_2 = Distance from c.g. to fin center of force.

When $N_1 + N_2 = N = g\,(C_{N\alpha})$

$$\frac{C_{N\alpha}}{C_{M\alpha_I}} = \frac{N_1 + N_2}{M_1 + M_2} = \frac{A}{B}$$

Note that for a statically stable projectile, BRL nomenclature assigns a negative value to $C_{M\alpha}$

$$\therefore \quad \ell_2 < 0.$$

For any changes in N, i.e., ΔN due to fin revision of any nature that does not produce a change in c.g. or ℓ_2,

$$\frac{C_{N\alpha}}{C_{M\alpha_{II}}} = \frac{N_1+N_2+\Delta N}{N_1\ell_1+N_2\ell_2+\ell_2\Delta N} = \frac{A+\Delta N}{B+\ell_2\Delta N}$$

and

$$\frac{\left(\frac{C_{N\alpha}}{C_{M\alpha}}\right)_I}{\left(\frac{C_{N\alpha}}{C_{M\alpha}}\right)_{II}} = \frac{\frac{A}{B}}{\frac{A + \Delta N}{B + \ell_2\Delta N}} = Z$$

$$\text{or} \quad Z = \frac{A}{B} \cdot \frac{B+\ell_2\Delta N}{A+\Delta N}$$

$$= \frac{1 + \frac{A}{B}\left(\ell_2\right)\left(\frac{\Delta N}{A}\right)}{1 + \frac{\Delta N}{A}}$$

$$= \frac{1 + c\,q}{1 + q}$$

where $c = \frac{A}{B}\,\ell_2$

and $q = \frac{\Delta N}{A}$

Figure A-2 plots this relation and indicates:

1. At $q = -1$, i.e., all lift removed, the accuracy ratio becomes infinite.

2. The real bounds on the accuracy factor are asymptotic to $z = c$.

3. The function is symmetrical about $q = -1$. Though not plotted, the region $q < -1$ (which represents a reversal in normal force direction, a boattail for instance) constitutes a possible solution to the equation.

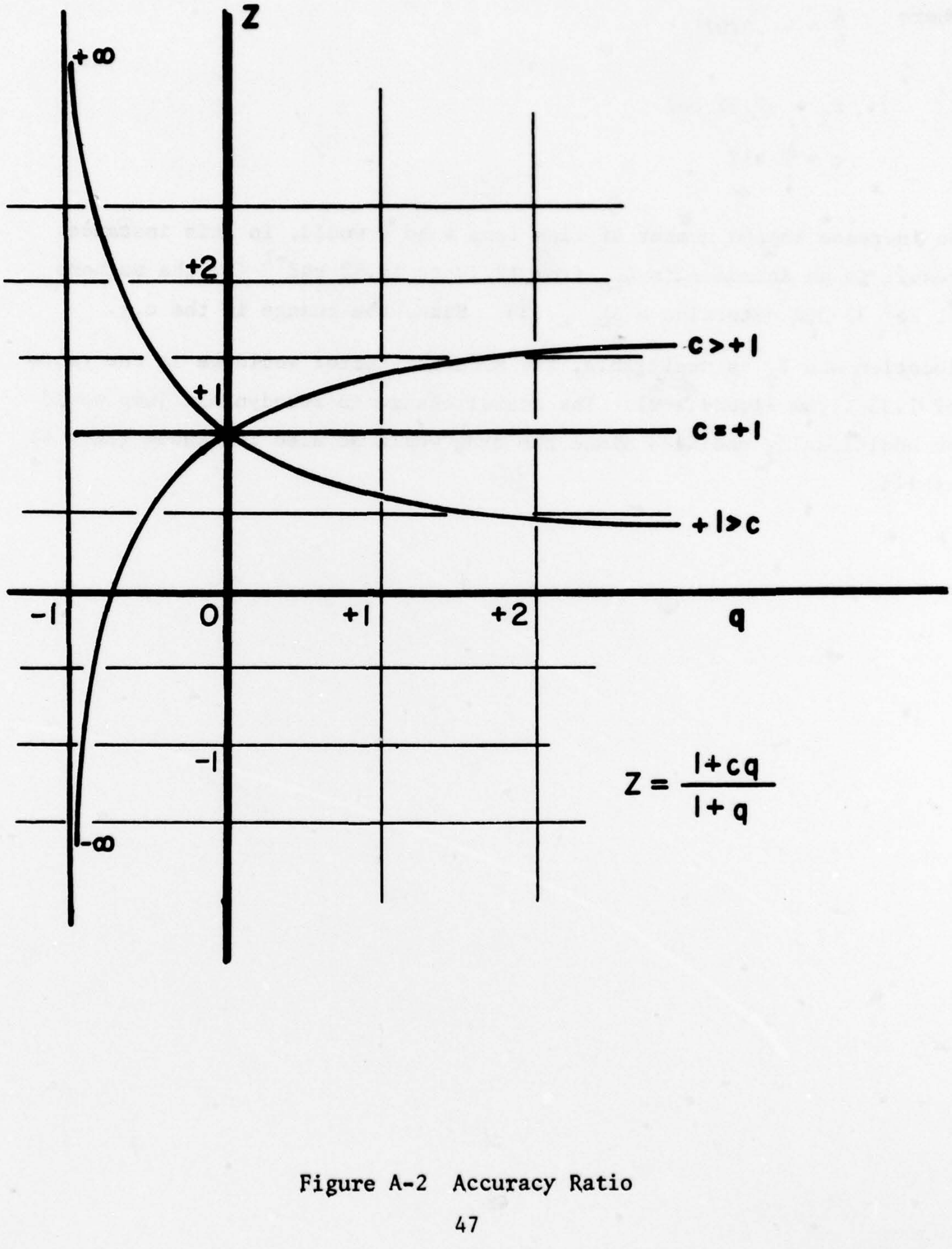

Figure A-2 Accuracy Ratio

Example:

Consider the flechette, Fig 2, at M = 4.5

where $\frac{A}{B} = -.3207$

$\ell_2 = -7.52$ cal.

$c = 2.412$

An increase in the number of fins from 4 to 6 would, in this instance, result in an increase in $C_{N\alpha}$ from 12.70 to 16.92 rad^{-1} (by the methods of Ref 3) and determine a $\frac{\Delta N}{A} = .33$. Since the change in the c.g. location and I_y is negligible, the accuracy factor would be in the ratio of 1.33 (from Figure A-2). The actual change in aerodynamic jump would be additionally modified since the drag would be also increased (Ref. 4) by 11%.

APPENDIX B

CALIBER NOMENCLATURE

Caliber nomenclature is widely used in aerodynamic expression as a dimensional convenience to compare performance parameters of geometrically similar models. It is usually referred to a linear scale representing the arithmetic ratio of a linear dimension to an arbitrary standard - most often the body diameter at the forward bourrelet - but has been employed to identify volumes*. Only a simple extension of the reasoning is required then to simultaneously de-dimensionalize the "mass" factor in a given expression (by dividing by a reference unit mass of water, 1g/cc for instance) and deduce a normalized system of mechanical units which permits a rational comparison of the dynamic properties of even geometrically dissimilar elements of machinery. Usually the context of discussion identifies the quantities as "mass cal", "inertia cal" "length cal", etc., although a complete lexicon of explicit and descriptive terms is available for this purpose.

In the present instance: (1) The particular contribution of the transverse moment of inertia to the aerodynamic jump term thus acquires commonality. (2) Within the subgroups of driving groove configuration, (extended or submerged) the mass in caliber notation is proportional to the frontal area density of the projectile and therefore constitutes an order of merit in assessing penetration potential. (3) The caliber of the mass is in inverse exponential proportion to the retardation and similarly allows direct comparison between projectiles in estimating velocity decrement.

In more general context, an appropriate illustration is shown by inspection of the gyroscopic stability criteria for spinning shell. The gyroscopic stability factor, S_g, is defined[1] as

$$S_g = \frac{\left(\frac{pd}{V}\right)^2 (2) \quad I_x^{\,2}}{\pi \rho \; I_y \; C_{M\alpha} d^5}$$

MacAllister, et al., "A Compendium of Ballistic Properties of Projectiles of Possible Interest in Small Arms", BRL Report No. 1532, February 1971, (AD #882117).

where:

S_g = gyroscopic stability factor

$\frac{pd}{v}$ = $\frac{2\pi}{n}$ where n is the rifle twist in cal/turn (note that this ratio is a pure number)

I_x = axial moment of inertia

I_y = transverse moment of inertia

$C_{M\alpha}$ = static moment coefficient

d = reference diameter

ρ = air density

These quantities are normalized by dividing the mass units (m) by the specific mass of water ($m_w \ell^{-3}$) and converting the linear dimensions to caliber notation to become:

$S_g = S_g$ (unchanged)

$\frac{pd}{v} = \frac{2\pi}{n}$ (unchanged)

$$I_x = K_1 \frac{m\,\ell^2}{m_w \ell^{-3}} = C_1 \quad \ell^5 \quad = \quad C_1 \text{ cal}^5 \quad \text{per unit mass of water}$$

$$I_y = K_2 \frac{m\,\ell^2}{m_w \ell^{-3}} = C_2 \quad \ell \quad = \quad C_2 \text{ cal}^5 \quad \text{per unit mass of water}$$

$$\rho_{air} = K_3 \frac{m_a \ell^{-3}}{m_w \ell^{-3}} = C_3 \quad \text{per unit mass of water}$$

$$d = K_4 \quad \ell \quad = \quad 1 \text{ Cal}$$

So that with K, the reciprocal of the linear physical unit:

$$S_g = \frac{8\,\pi C_1^{\,2}}{C_2 C_3 C_{M\alpha} n^2}$$

$$= 20910\,\frac{C_1^{\,2}}{C_2 C_{M\alpha} n^2}$$

The physical properties and the known aerodynamic performance of a range of projectiles from 0.17 inch to 20mm diameter are compiled in a report by W.F. Braun*. Reducing these physical properties to caliber notation permits the full scale of data to be presented by the nomograph, Figure B-1, for which separately determined data to 155 mm diameter shell are also assembled.

An example of an S_g determination is presented on the nomograph.

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*W. F. Braun, "Aerodynamics Data for Small Arms Projectile," BRL Report No. 1630, January 1973, (AD #9095757).

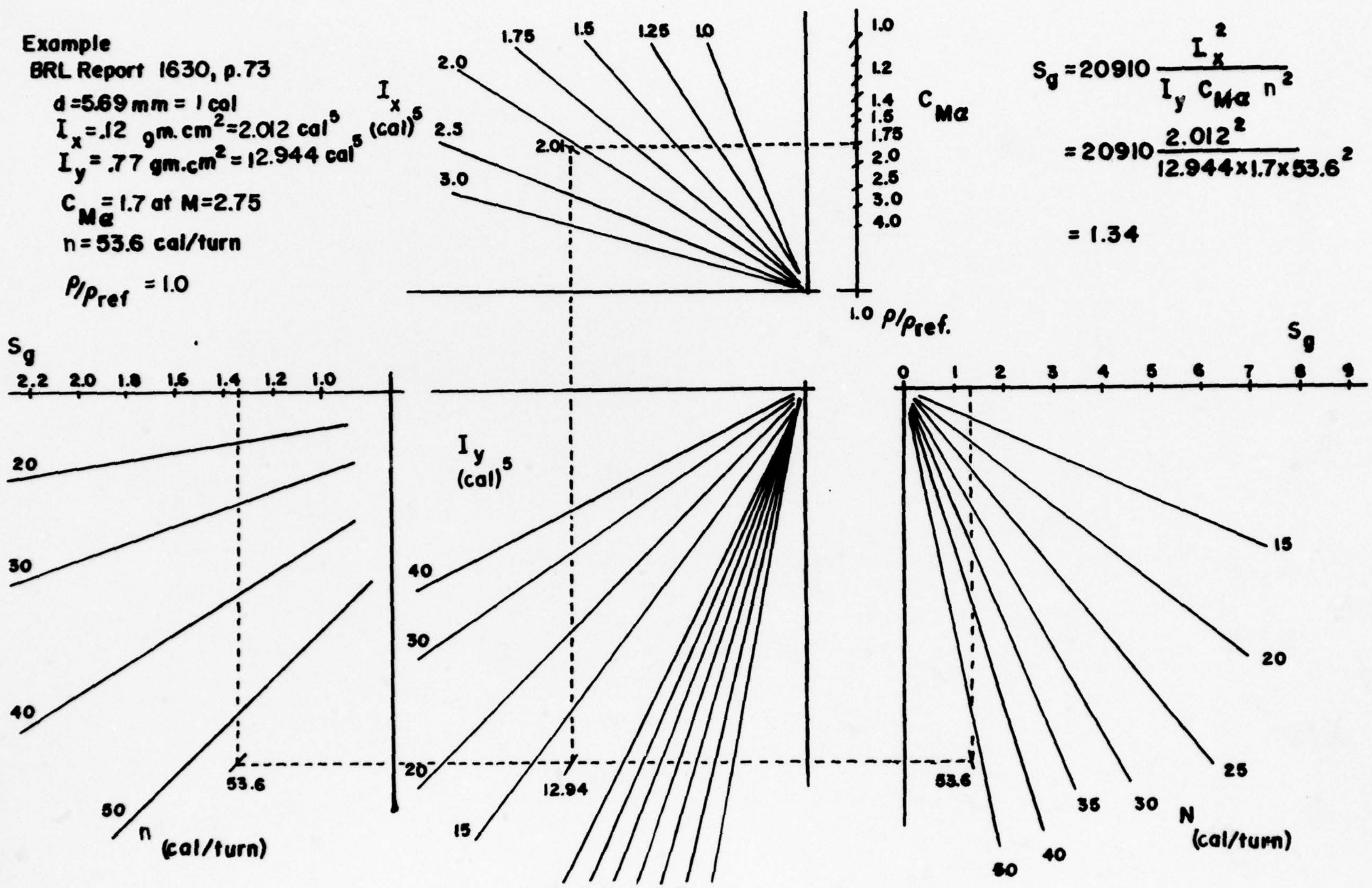

Figure B-1 Nomograph for S_g

APPENDIX C

NOMOGRAPH FOR J_ζ

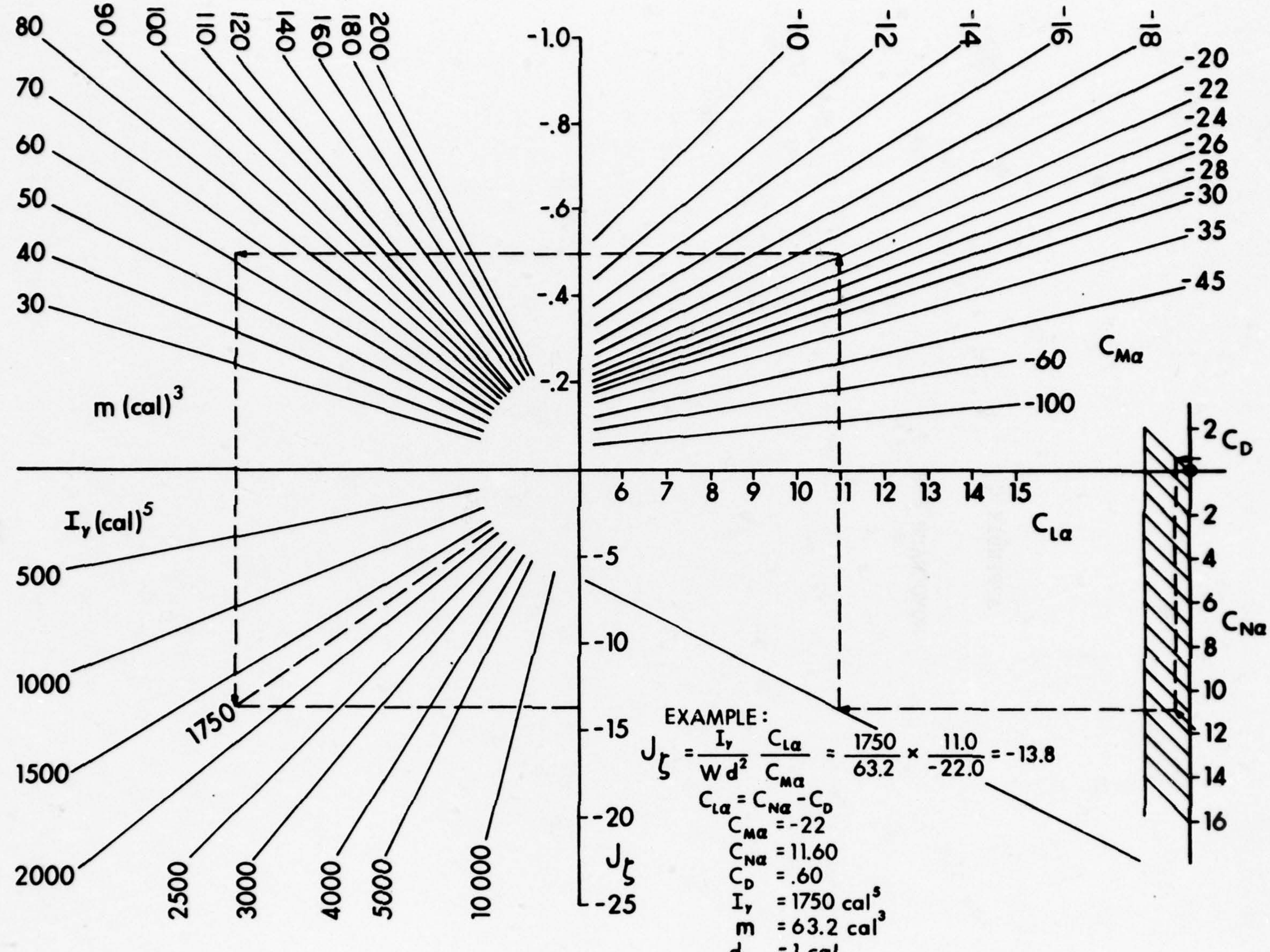

Figure C-1 Nomograph for J_ζ

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